

PERFORMANCE REPORT  
**A Cockroach-Like Hexapod Robot  
for Natural Terrain Locomotion**

Grant N00014-96-1-0708

Period of Performance: 3 Years

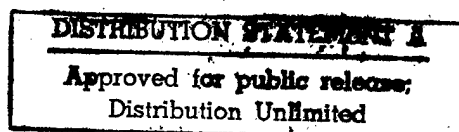
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## Research Progress

- Using our dynamic simulation of the robot, a posture controller has been developed based upon the Virtual Model control scheme. The problem of redundant kinematics (e.g. the front legs have 5 actuated joints where only 3 are needed to place the foot in a particular location) is solved using an optimization approach. This posture controller does not just control static posture but is the major component of a dynamic locomotion controller that is now being developed. The robot has complex cockroach-like kinematics, yet the controller effectively manages its posture despite large perturbations. The notions used to develop the controller are supported by ongoing research in physiology. For example, Horak and Macpherson (Handbook of Physiology, 1996) are investigating how control responsibility for posture and locomotion is distributed throughout the nervous system. Their research indicates that posture control is more than local reflex interaction, but the orchestration and tuning of these reflexes according to some central desired behavior. Discussions with Macpherson at the Neurosciences meeting led to more detailed discussions hosted by Sasha Zill at Marshall Univ.

- Strain gages have recently been fixed to the proximal ends of the tibias of Robot III to provide load information necessary for walking. These load sensors model campaniform sensilla found in the cockroach at a similar location (as well as in many other locations on the animal's legs).

- We have related kinematics and motor activity of middle and hind legs during climbing over a barrier (transparent block). During the rearing stage of climbing, the animal rotates the middle leg, raising the body up so that extension of the rear legs pushes the animal over the block. To make the rear leg extension more effective, a rotation of the tibia relative to the body also occurs in the hind leg. This tibia rotation requires flexion of the trochanter-femur joint, a joint previously thought to be fused because it does not rotate like the other joints of the leg. Instead, it flexes along an approximately 45° angle across the leg. This rotation also appears to be critical to the swing phase of walking.

- We have begun to analyze another behavior that reveals the degree of adaptive variability available to the animal: climbing on a monofilament ladder. The problems facing the animal are: (a) the animal is climbing vertically, (b) the substrate is discontinuous, so that the animal must search for a foothold, (c) the filaments are compliant. Our preliminary findings on this behavior indicate that the role of front and rear legs switch. Front legs pull the animal up providing the major force for movement, while the hind legs seem to balance the animal and go through searching movements similar to the front legs during walking. This suggests that the animal can alter control strategies for each leg.

- A student (Andrew Tryba) has developed a preparation that should allow detailed observations of the cellular basis of the switch between tripod gait movements and searching.

The animal is tethered on a set of pins that allow some up and down movement. The animal is set over a lightly greased plate and will make apparently normal tripod gait movements. If the substrate is then dropped, unloading the legs, the animal will repeatedly switch from walking to searching movements, especially in the middle legs.

- Our analysis of evolved model central pattern generators (CPGs) has been extended to a population of 325 3-, 4- and 5-neuron circuits. We have demonstrated that an analysis in terms of dynamical modules generalizes to a large population of 3- and 4-neuron CPGs, although it begins to break down for 5-neuron CPGs. A detailed analysis of the biomechanical properties of the model body explains many features of the evolved CPGs. This biomechanical analysis, along with our understanding of the dynamics of these model neurons, allowed us to account for a large fraction of the architectural and parameter variability observed in the 3-neuron CPGs.

- We have performed an extensive simulation study of the stick-insect-based distributed locomotion controller that we have utilized in our robots. These studies have characterized how the relative phases of the legs change as the ratio of retraction to protraction velocity is varied. In addition, we have studied how these relative phase curves vary with coupling weights, and we have discovered several bifurcations that arise. A smooth 12-dimensional model of Cruse's original discontinuous, discrete-time controller has been formulated, and we have begun to analyze phase-locking in this model.

## Publications

Beer, R.D. (1997). The dynamics of adaptive behavior: A research program. *Robotics and Autonomous Systems* 20:257-289.

Beer, R.D., Chiel, H.J. and Gallagher, J.C. (submitted). General principles and individual variability in evolved model CPGs for walking: Neural and biomechanical constraints. Submitted to *J. Neurophysiology*.

Chiel, H.J. and Beer, R.D. (1997). The brain has a body: Adaptive behavior emerges from interactions of nervous system, body and environment. *Trends in Neurosciences* 20: 553-557.

Chiel, H.J., Beer, R.D. and Gallagher, J.C. (submitted). Dynamical modules in an evolved model CPG for walking. Submitted to *J. Neurophysiology*.

Flannigan, W. C., Nelson, G. M. and Quinn, R. D., "Locomotion Controller for a Crab-like Robot," submitted to the 1998 IEEE International Conference on Robotics and Automation (ICRA'98) Video Proceedings.

Nelson, G. M., Bachmann, R. J. Quinn, R. D., Watson, J. T., A. K., Ritzmann, R. E., "A Cockroach-like Robot," submitted to the 1998 IEEE International Conference on Robotics and Automation (ICRA'98) Video Proceedings.

Nelson, G. M. and Quinn, R. D., "Posture Control of a Cockroach-like Robot," submitted to the 1998 IEEE International Conference on Robotics and Automation (ICRA'98).

Ritzmann, R.E. and R.C. Eaton (1997) Neural substrates for initiation of startle responses. in *Neurons, Networks, And Motor Behavior* eds. Paul S.G. Stein, Sten Grillner, Allen I. Selverston, and Douglas G. Stuart, MIT Press. pp 33-44.

Vaidyanathan, R., Chiel, H. J., and Quinn, R. D., "A Hydrostatic Robot for Marine Applications," submitted to the 1998 IEEE International Conference on Robotics and Automation (ICRA'98) Video Proceedings.

Watson, J.T. and R.E. Ritzmann (1997) Leg kinematics and muscle activity during treadmill running in the cockroach, *Blaberus discoidalis*: I. Slow running. *J. Comp. Physiol.* (in press).

Watson, J.T. and R.E. Ritzmann (1997) Leg kinematics and muscle activity during treadmill running in the cockroach, *Blaberus discoidalis*: II. Fast running. *J. Comp. Physiol.* (in press).

## Presentations

R.J. Bachmann, "Development of a Cockroach-like Robot", ONR progress meeting run by Sasha Zill, New Orleans, October 19, 1997.

R. Beer gave an invited presentation at the Fall Science Symposium, Santa Fe Institute, Santa Fe, NM, Oct., 1997.

H. Chiel gave a seminar in the Dept. of Neuroscience, School of Medicine, Case Western Reserve University, Nov., 1997.

H. Chiel gave an invited talk at the Network Modeling Symposium, 5th International Conference on Invertebrate Neurochemistry and Neurophysiology, Eilat, Israel, Sept., 1997.

Y. Endo, "Development of a Model Car for Implementation of Crash Avoidance System", Graduate Student Seminar, CWRU, October 1997.

W.C. Flannigan, "Structural Modeling of Cockroach Trochanter", ONR progress meeting run by Sasha Zill, New Orleans, October 19, 1997.

C.D. Jeong, "Crash Avoidance System Based Upon the Cockroach Escape Circuit", Graduate Student Seminar, CWRU, October 1997.

R. Ritzmann gave a seminar to the "Engineering Awareness for High School Teachers" Program, Case Western Reserve University, Dec., 1997.

R.D. Quinn, "Biologically-Inspired Robotics at CWRU", Case Club, Akron Chapter, October 7, 1997.

R.D. Quinn, "Biologically-Inspired Robotics at CWRU", President's Weekend, CWRU, October 31, 1997.

R.D. Quinn, "Mechanical model of cockroach leg", ONR progress meeting run by Sasha Zill, New Orleans, October 19, 1997.

R.D. Quinn, "Biologically-Inspired Control Systems", Intelligent and Flexible Systems Workshop, 1997 International Mechanical Engineering Congress and Exposition, Dallas, November 19, 1997.

Bio-Robotics Lab personnel: "Biologically-Inspired Robotics at CWRU", CWRU open houses and other group tours for high school students and "Friends of the University", October 26, November 3, November 22, November 25, December 2, 1997.

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